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Investigation of the starting process of free-piston engine generator by mechanical resonance

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Abstract

As an alternative to conventional engines, free-piston engine generator (FPEG) is a promising power generation system due to its simplicity and high thermal efficiency. One crucial technical challenge in the FPEG operation is the initial process of overcoming the compression force to achieve a certain speed which allows a stable and continuous operation, i.e. starting process. This paper proposes a novel method to start the engine by mechanical resonance. A closed-loop control model was developed and implemented in a prototype FPEG which was driven by a linear machine with a constant driving force. Both numerical and experimental investigation was carried out. The results show that once the linear motor force have overcome the initial friction force, both the in-cylinder peak pressure and the amplitude of the piston motion would increase gradually by resonance and quickly achieve the target for ignition. With a fixed motor force of 110N, within 0.8 second, the maximum in-cylinder pressure can achieve 12 bars, the compression ratio can reach 9:1, and the engine is ready for ignition. The results demonstrated that it is feasible to start the FPEG by mechanical resonance in a constant motor force in the direction of the natural bouncing motion.

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Key words: free-piston engine, linear machine, starting process

Nomenclature

x	Displacement of mover and piston
m	Moving mass including the mover of linear machine and two pistons
F_m	Electric linear motor force
F_l	Gas force from the left cylinder
F_f	Friction force
P	In-cylinder gas pressure
V	In-cylinder gas volume
γ	Adiabatic constant.

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1. Introduction

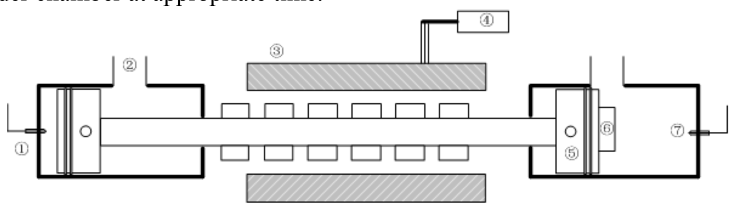
Free-piston engine generator (FPEG) is a new kind of energy conversion device, which integrates a linear combustion engine and a linear electrical machine into a single unit. As an alternative to conventional engines, FPEG is a promising power generation system and has attracted considerable research interests recently all over the world [1]. Combustion in the chambers of the engine makes the translator reciprocate in an almost resonant way and the linear electrical machine converts some of the mover's kinetic energy to electrical.

One crucial technical challenge in FPEG operation is the initial process of overcoming the compression force to achieve a certain speed which allows a stable and continuous operation, i.e. starting process. However, few detailed investigations on the starting process have been reported, as most of the research work concentrate on the design, simulation or performance prediction of FPEG in stable operation. One practical method to start the engine is to uses the electrical energy coupled with effective control strategy to produce the required force. The linear machine is operated as a linear motor during starting process and will be switched to a linear generator after ignition. Different control methods have been studied to allow operation of the electric machine as a motor for starting purposes [1-5]. However, the implement of an effective starting strategy to a prototype is still need to be acknowledged.

This research focuses on a spark ignited dual free-piston engine generator and proposes a novel method to start the engine by mechanical resonance. A control model will be developed and implemented in a prototype FPEG which is driven by a linear machine with a constant driving force. Numerical simulation of the starting process of FPEG will be developed in Matlab/Simulink to predict the basic performance of the engine, and closed-loop control strategy will be investigated. Furthermore, experiment will be carried out with the proposed starting method implemented into the prototype. Both the simulation and experiment were conducted without combustion process, which means the ignition system is disenabled during the investigation of the starting process.

2. Analysis of starting methods by linear machine

A dual free-piston engine generator in Fig.1 is proposed; it is a spark ignited dual FPEG and runs on a two-stroke cycle, employing the scavenging mode. The main parts of the engine are two combustion engines and a linear electric machine. The linear machine is operated as a linear motor during starting process and will be switched to a generator after ignition. A linear magnet mover with pistons at each end is placed between two opposing combustion chambers, which is the only moving part of the engine. The stator of the linear machine is connected with load to absorb the electricity generated by the linear machine during generating process. The carburettor is used to transport the air fuel mixture into the cylinder chamber at appropriate time.



①Spark plug ②Exhaust port ③Linear machine ④Load ⑤Piston ⑥ Scavenging port ⑦Cylinder

Fig.1 Free-piston engine generator

Scavenging is provided by scavenging pump, where intake ports, exhaust ports and scavenging ports are opened / closed by the moving piston itself. When both of the exhaust port and scavenging port are closed, the compression stroke will start, and fresh charge will be drawn into the scavenging pump from the intake port. As the piston approaches top dead center, combustion is initiated and high pressure gas push the piston down. When the exhaust port is uncovered, most of the burnt gases exit the cylinder. Then the scavenging ports are uncovered, the fresh charge which has been compressed in the scavenging pump flows into the cylinder.

During the starting process, the linear machine work as a linear motor and FPEG will be driven by the linear motor with a constant force. The mover with pistons will oscillate back and forth freely between its two endpoints. The basic performance parameters of the FPEG configuration are summarised in Table 1, and stork of the engine is viable. In order start the engine by mechanical resonance, the linear machine needs to be controlled to output constant motor force. Constant linear motor force can be implanted in closed-loop control strategy, which will be further investigated in the follow chapter.

Table 1 Free-piston engine specifications

Parameters	Value	Unit
Bore	52.5	mm
Stroke	70.0	mm
Moving mass	5.0	Kg

3. Simulation for starting process by mechanical resonance

Without ignition, the in-cylinder air is compressed and expanded as the piston moves back and forth of the cylinder, absorbing and dissipating energy respectively, exhibiting air-spring behaviour. Assuming a system consisted of a mass and two mechanical springs, the mass is connected with two opposed mechanical springs, and that other side of those springs is fixed, which is illustrated in figure 2.

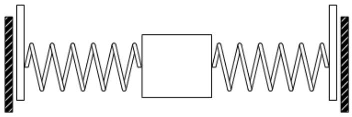


Figure 2 Mechanical spring mass system

The two springs are at its natural state at the beginning, and a constant force will be acted on a mass of 5kg, and it will be in the direction of the mass velocity to simulate the mechanical resonance phenomenon. Friction and other kind of unknown energy consumption are ignored in the simulation, the stiffness of the spring is set to 10000, its natural length is set to 100m, and the acted constant force is assumed to 30N. The numerical calculation result is as below:

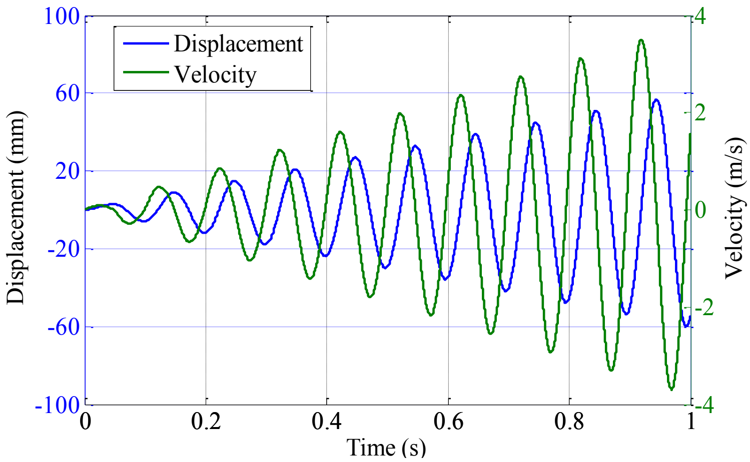


Figure 3 Mechanical resonances for spring system

It is clear to see that, within the 1 second observation time, both of the displacement amplitude and the maximum velocity of the mass in the mechanical spring system mentioned above grow from the initial small amplitude. As the compressed air in the cylinder is capable of creating a bounce phenomenon at each end of the stroke, which can be operated as mechanical spring. Thus, if very little energy is lost in the compression process, it is possible to apply a constant linear motor force of low but sufficient value to reciprocate the piston assembly in small amplitudes initially. The displacement amplitude and speed of the piston is expected to grow, and finally achieve the required pressure for ignition. In the starting process, the direction of the motor force is always the same as the velocity of the mover, which can be achieved by the driver of the linear machine.

In the starting process, mechanical forces acting on the pistons are identified as gas force from left cylinder, gas force from right cylinder, linear motor force, mechanical friction and inertial force of the mover [6-8]. A dynamic equation of the mover is derived, and simulation is implemented in Matlab/Simulink. The piston motion can be derived from Newton's second law, which is

$$F_m + F_l - F_r - F_f = m\frac{d^2x}{dt^2} \tag{1}$$

A subsystem block is developed to simulate the motor force with velocity detector of the mover. This is used to ensure that the output force of the linear machine is always in the same direction with the piston's motion during starting process. The ideal relationship between in-cylinder air pressure and volume is listed below, which is sufficient for the present modelling and simulation of the starting process after the exhaust port is closed. The subscripts 1 and 2 represent the values of P and V at different times or displacements.

$$P_1V_1^{\gamma} = P_2V_2^{\gamma} \quad (2)$$

Considering the elimination of the conventional crank mechanism, the pistons of FPEG is free of side force. The friction force is small compared with the linear motor force during starting process, and will not have significant influence on the engine dynamics. Because of this, the friction force is assumed to be constant over the full process, and is taken as 60N. Although motor force is produced by electrical current injection, it is simulated just as other mechanical forces contributing to the total net force. A subsystem is developed in Matlab/Simulink to produce motor force in the same desired direction with mover's motion. Figure 4 shows the simulation results with a motor force of 110N.

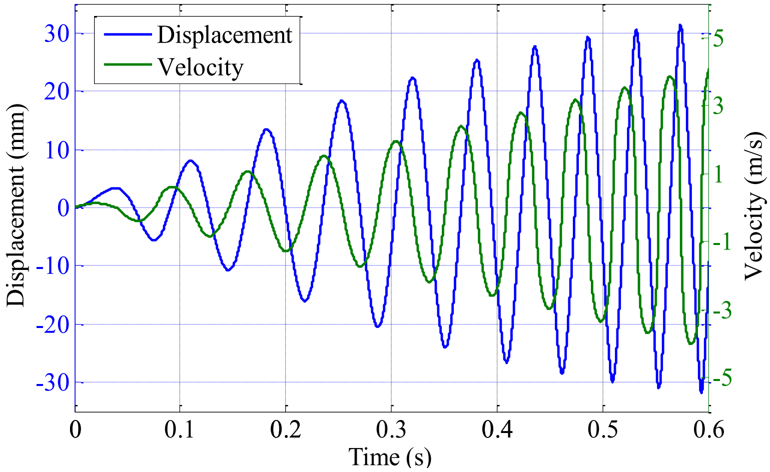


Figure 4 Simulation results with fixed motor force of 110N

It demonstrates that, if the motor force is sufficient enough to overcome the friction and constantly applied in the direction on mover's motion, the amplitude of the piston's displacement grows and can be resonated to approximately the whole stroke length of 70mm. Moreover, the peak in-cylinder gas pressure and maximum piston velocity for each circle is expected to grow with the piston amplitude. As a result, it is possible for the engine to achieve a very high compression ratio and in-cylinder pressure during starting process, confirming the viability of the starting strategy by mechanical resonance.

4. Experimental research for closed-loop control strategy

The proposed starting method is implemented into the prototype and the ignition system is disenabled during the experiment. As compression ratio and in-cylinder gas pressure are regarded as two important factors for ignition, the targets we set for a successful starting process are listed below:

a. To achieve a maximum in-cylinder pressure of 10 bar with reasonable speed;

b. To reach an effective compression ratio of 9:1.

The control system for the validation of closed-loop strategy on the starting process is consisted with three parts, which are Programmable Multi-Axis Controller, stand-alone drive and the linear machine. The control system is coupled with PID compensators to reduce the influence from back electromagnetic voltage, so the electric machine will output a constant motor force in direction of the mover's velocity. The in-cylinder gas pressure acquisition is implemented on National Instruments' PXI embedded controller and LabView Real Time software. The piston's displacement is collected through the internal position sensor of the linear machine The constant motor force is set to 110N.The FPEG prototype is combined with dedicated bench of steel plates, constructed to reduce the severity of vibrations during testing. The experimental results of the piston displacement and the in-cylinder gas pressure for right side are demonstrated in Figure 5 and Figure 6 respectively.

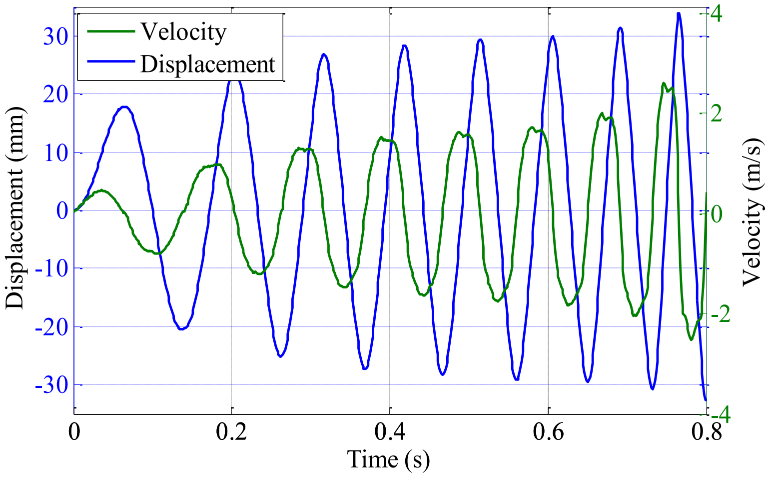


Figure 5 Experimental results of piston's displacement and velocity

They indicate that, despite the friction, air leakage, heat transfer, vibration as well as other kind of energy consumption, the amplitude of the piston motion, the maximum piston velocity as well as the peak in-cylinder peak pressure would increase gradually by resonance and quickly achieve the target for ignition. Within 0.8 second, the piston is reciprocated to approximately the whole stroke length and the peak in-cylinder pressure can achieve 12bars. Furthermore, the speed of the engine during starting process by the proposed method is about 800 cycles per minute, which is feasible for ignition compared with the required starting speed for conventional engine. Moreover, the speed of the piston for the first few cycles during the starting process is much lower than 800 cycles per minute, but will get faster afterward.

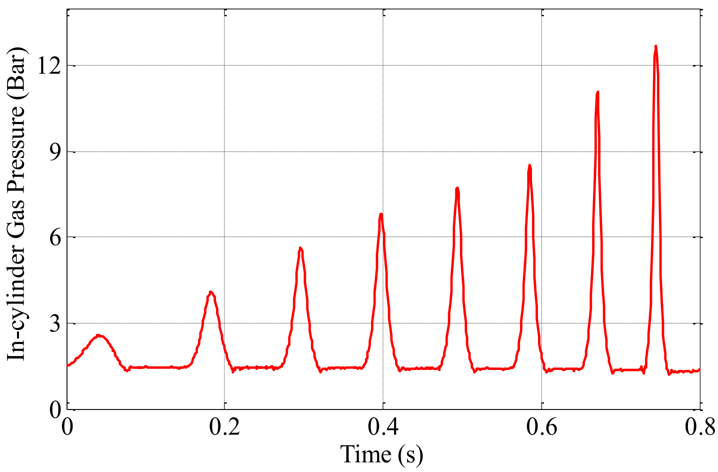


Figure 6 Experimental results of In-cylinder pressure

5. Conclusion

The simulation and experimental results demonstrated that once the linear motor force have overcome the initial friction force, both the in-cylinder peak pressure and the amplitude of the piston motion would increase gradually by resonance and quickly achieve the target for ignition. It is feasible to start the FPEG by mechanical resonance in a constant motor force in the direction of the natural bouncing motion.

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